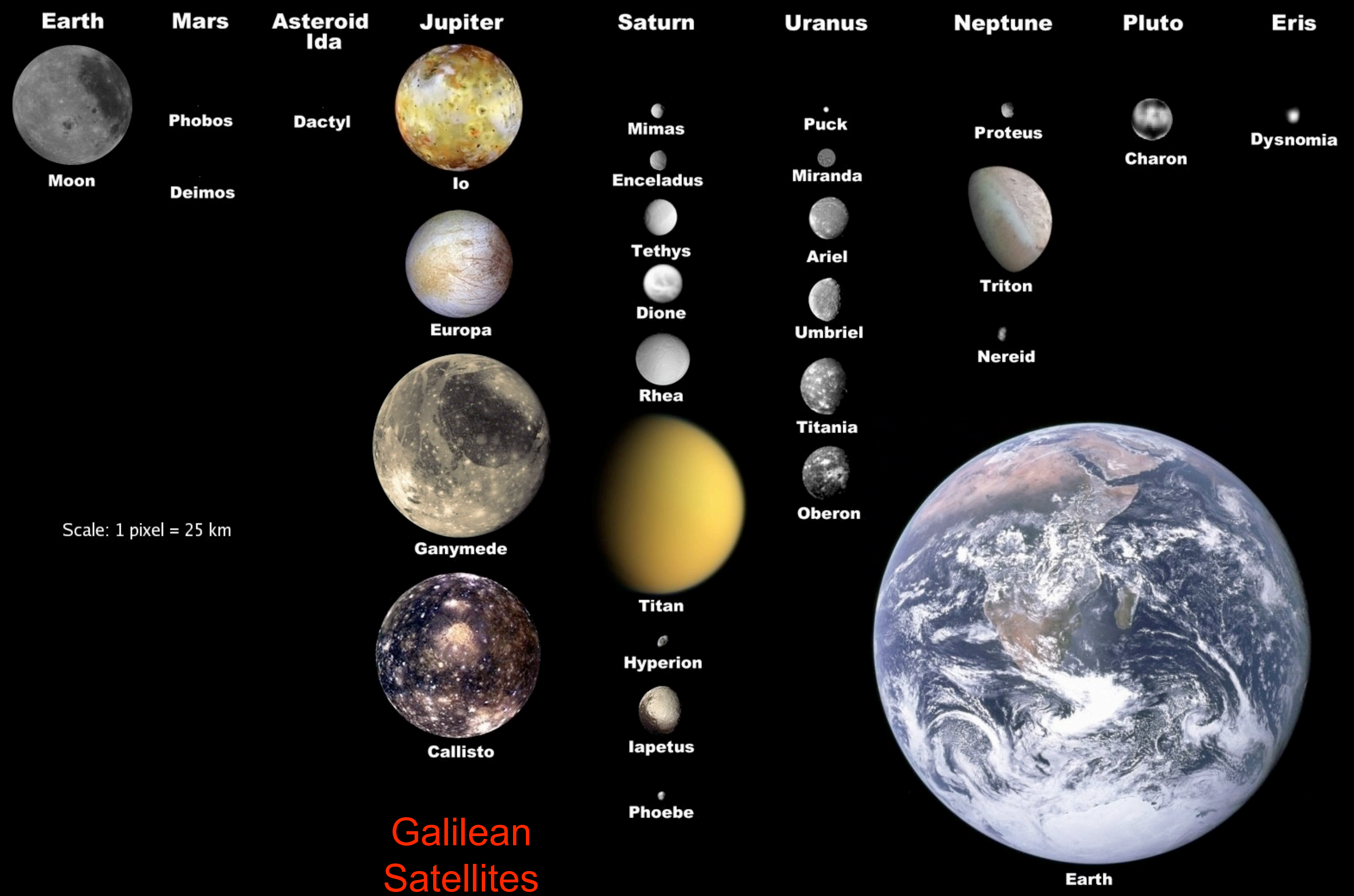
Formation and Evolution of Satellite Systems

Man Hoi Lee 李文愷 (*HKU*)

Collaborators:
Neal Turner (*JPL*), Takayoshi Sano (*Osaka*);
W. H. Cheng (*HKU*), Stan Peale (*UCSB*)

Selected Moons of the Solar System, with Earth for Scale



Galilean Satellites

Satellite Systems

- Regular satellites of Jupiter, Saturn, and Uranus:
  - Prograde orbits nearly coplanar with planet’s equator plane.
  - a up to tens of R_p
  - $M_{tot}/M_p = 1.1 - 2.5 \times 10^{-4}$
  - Formation in circumplanetary disk
- Earth-Moon and Pluto-Charon:
  - $M_s/M_p \approx 1/80$ and $1/9$
  - $a/R_p = 60$ an 17
  - Pluto-Charon dual synchronous
  - Giant impact origin

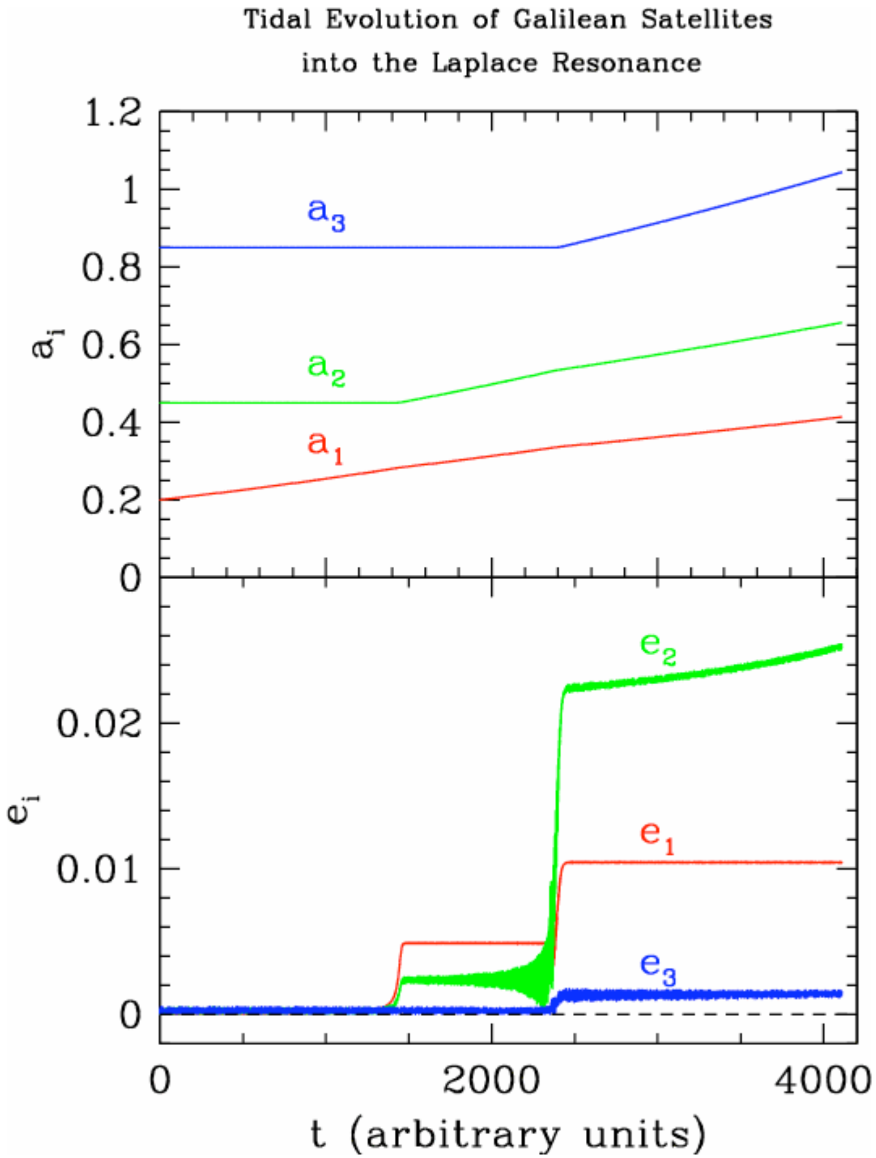
Formation of the Galilean Satellites

- Constraints:
  - Ganymede and Callisto about half rock and half ice.
  - Callisto only partially differentiated ($I/MR^2 \approx 0.355$; Anderson et al. 2001).
- Formation scenarios:
  - Gas poor planetesimal capture model (Safronov et al. 1986; Estrada & Mosqueira 2006).
  - Minimum mass subnebula model (Lunine & Stevenson 1982; Takata & Stevenson 1996; Mosqueira & Estrada 2003).
  - Gas-starved subnebula model (Canup & Ward 2002).

- Nature of mass and angular momentum transport in subnebula is a major uncertainty in modeling satellite origins.
- Turbulence driven by Magneto-Rotational Instability (MRI) provides transport if gas is sufficiently ionized to couple to the magnetic fields.

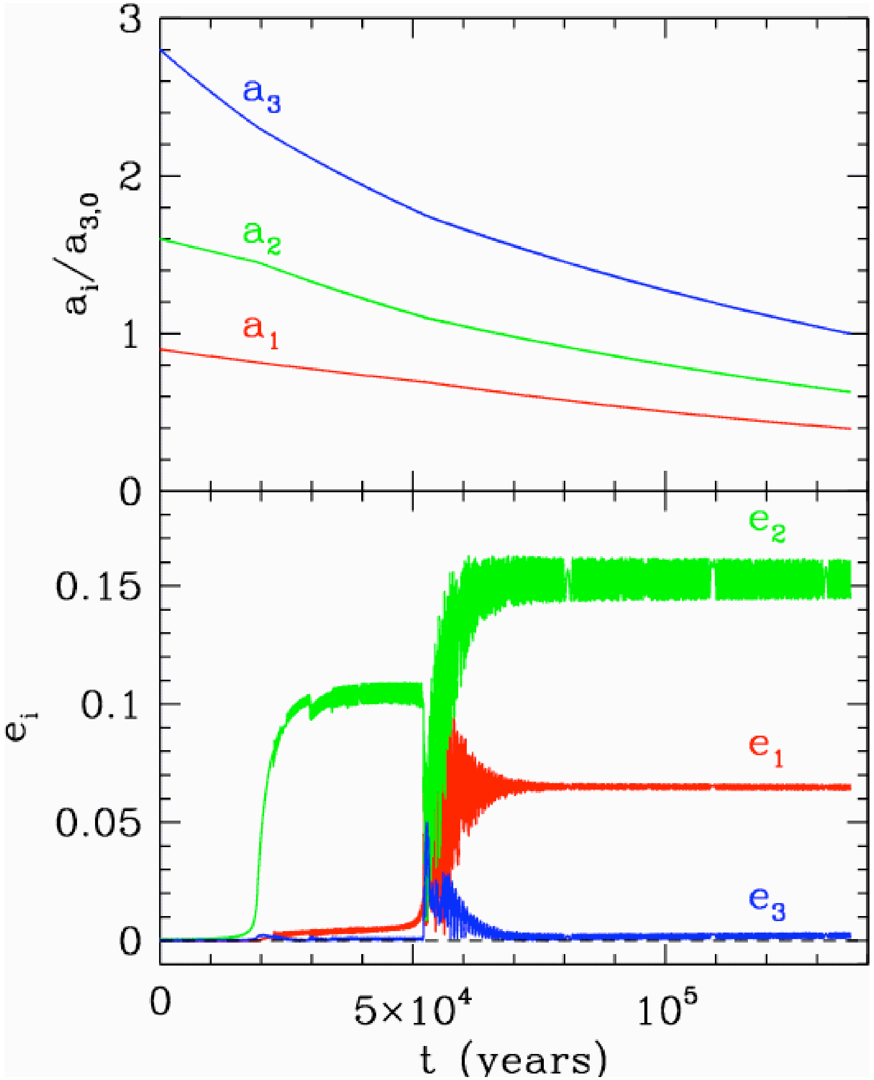
Origin of the Laplace Resonance: Tidal or Primordial?

- Orbits of Io, Europa, and Ganymede are in the Laplace resonance, with orbital periods nearly in the ratio 1:2:4.
- Resonances could be assembled inside-out long after the formation of the satellites by tidal expansion of orbits (Goldreich 1965, Yoder 1979, Yoder & Peale 1980).

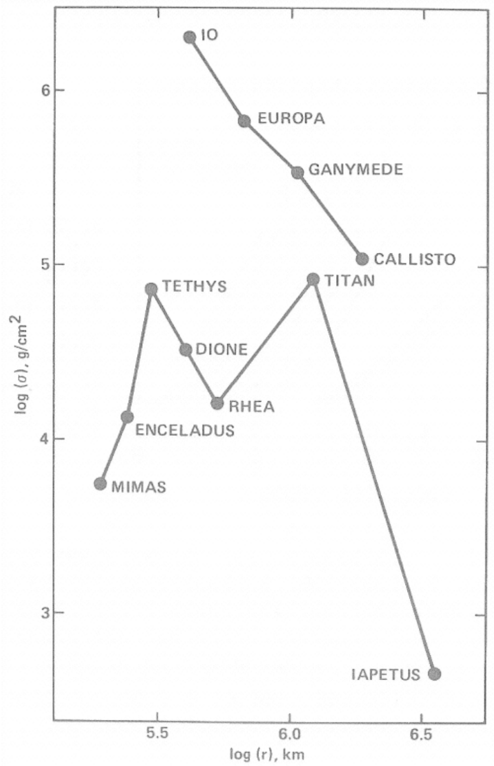


- Alternatively, resonances could be assembled outside-in during satellite formation by the differential migration of satellites due to interactions with circumjovian disk (Peale & Lee 2002; Sasaki, Stewart & Ida 2009).
- Probability of capture into the observed Laplace resonance could be sensitive to circumjovian disk model.

Nebula Induced Evolution of Galilean Satellites into Laplace Resonance

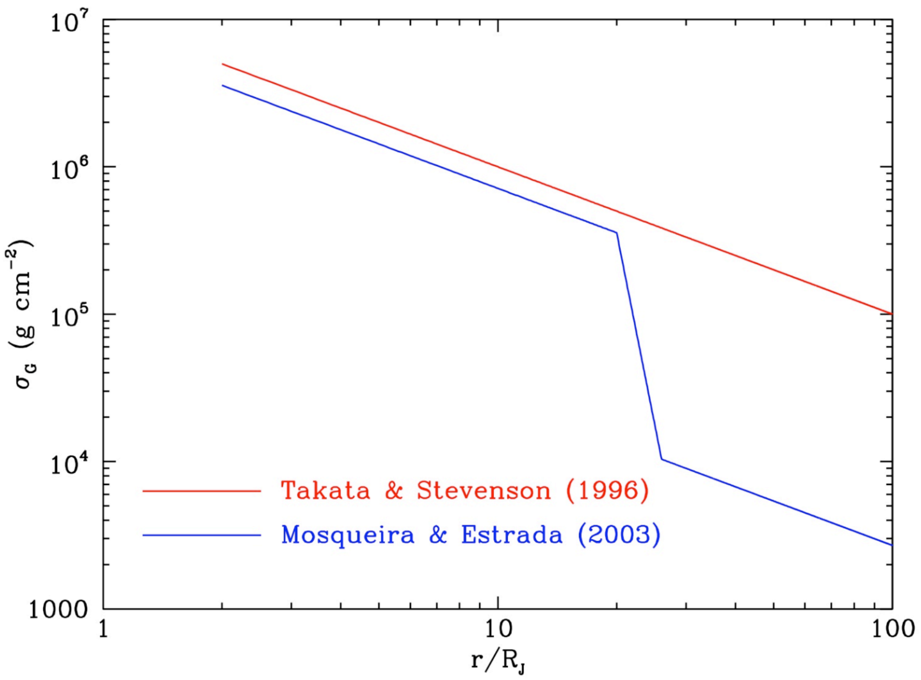


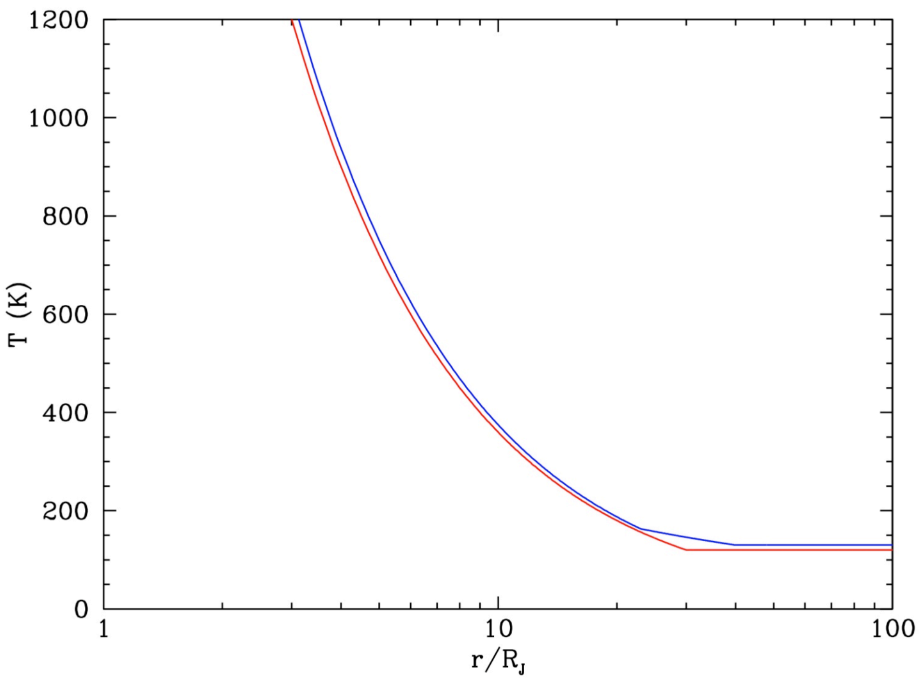
Minimum Mass Subnebula Model



(Pollack & Consolmagno 1984)

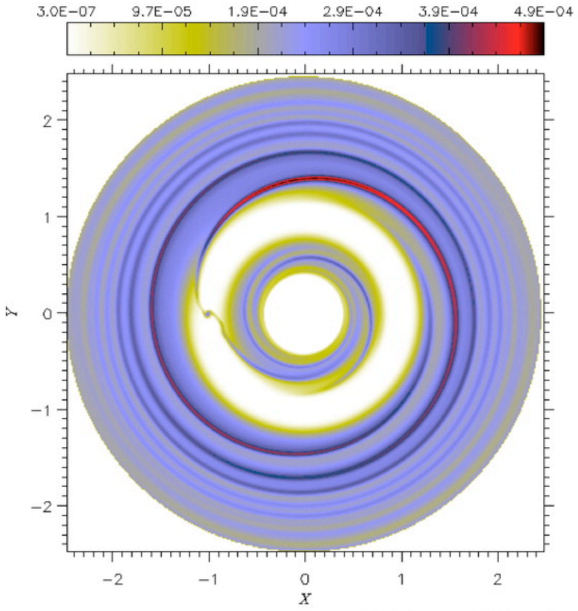
- Analogous to minimum mass solar nebula.
- Galilean satellites + enough volatiles for Solar abundance.

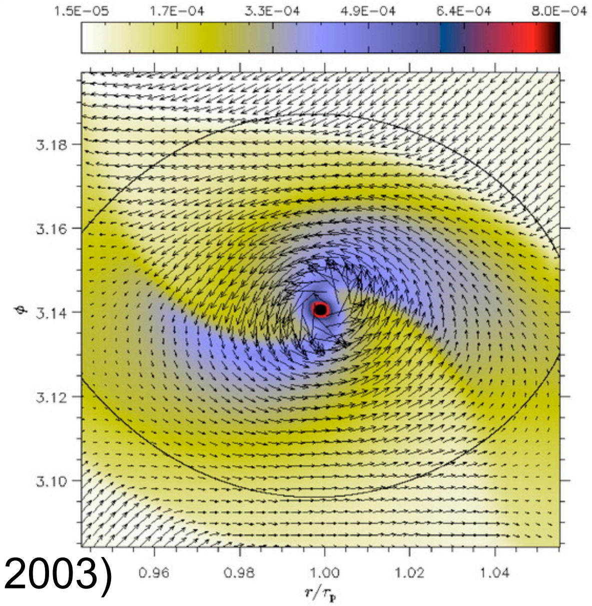




- Very high gas surface density $\sigma_G \sim 1/r$.
- Sharp drop in σ_G at $r/R_J \approx 23$ in the Mosqueira & Estrada (2003) model.
- Temperature $T \sim 1/r$ at $r/R_J < 30$ and ~ constant at $r/R_J > 30$.

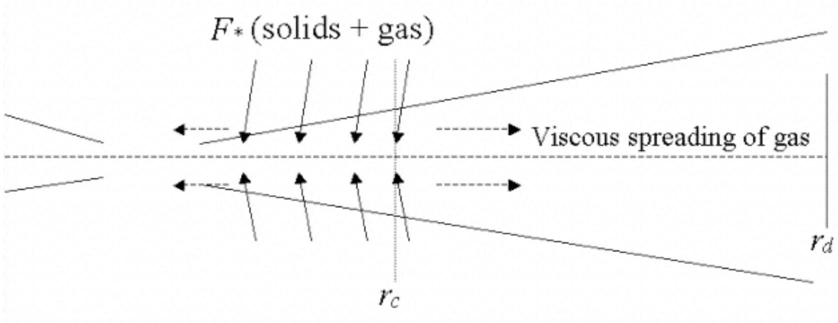
Gas-starved Subnebula Model





(D’Angelo et al. 2003)

- Not all mass needed to form the satellites in the disk all at once.
- Replenished by slow inflow of gas and solids from the solar nebula after Jupiter opens a gap.

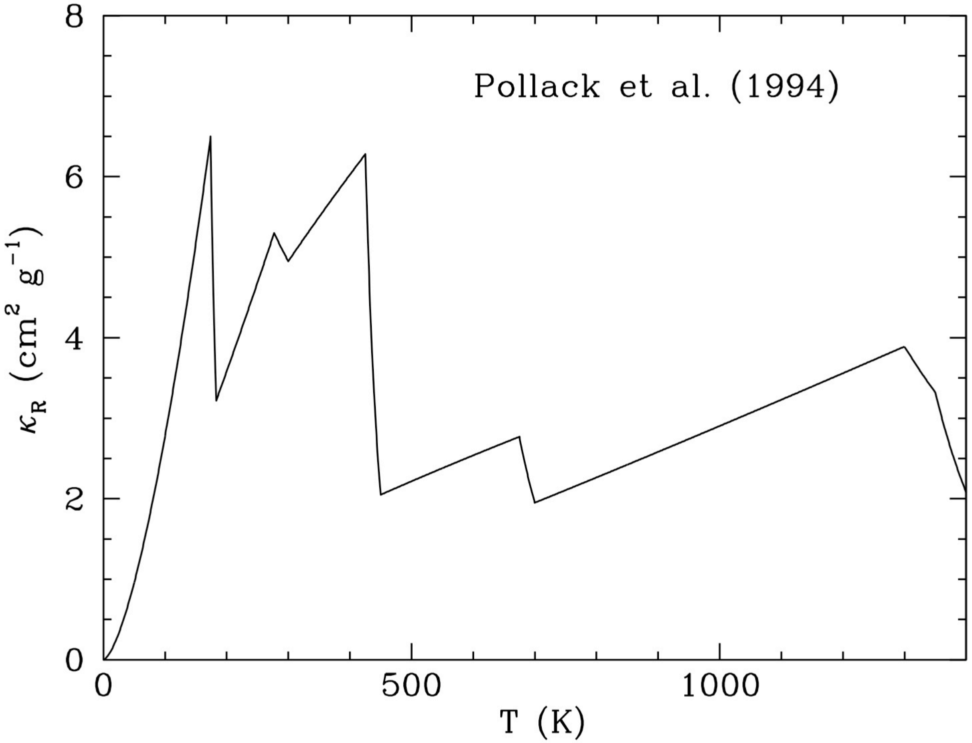


(Canup & Ward 2002)

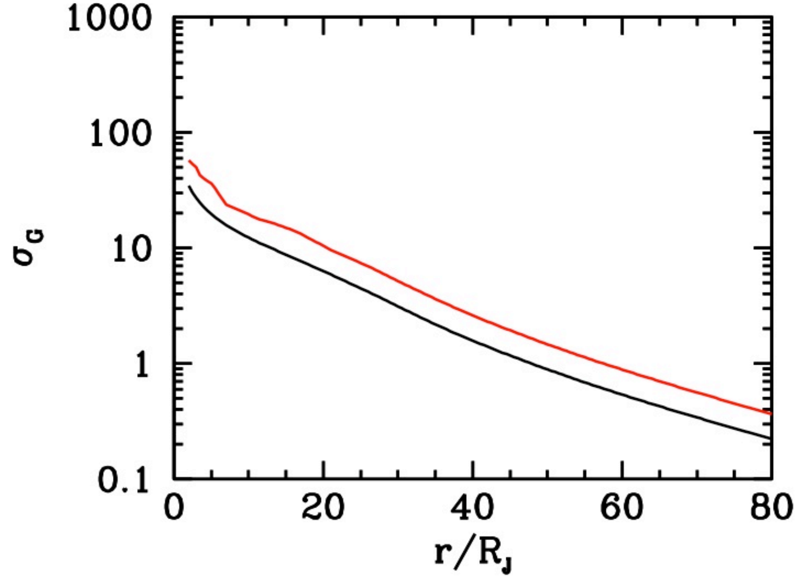
We have constructed Improved Gas-starved Subnebula models with

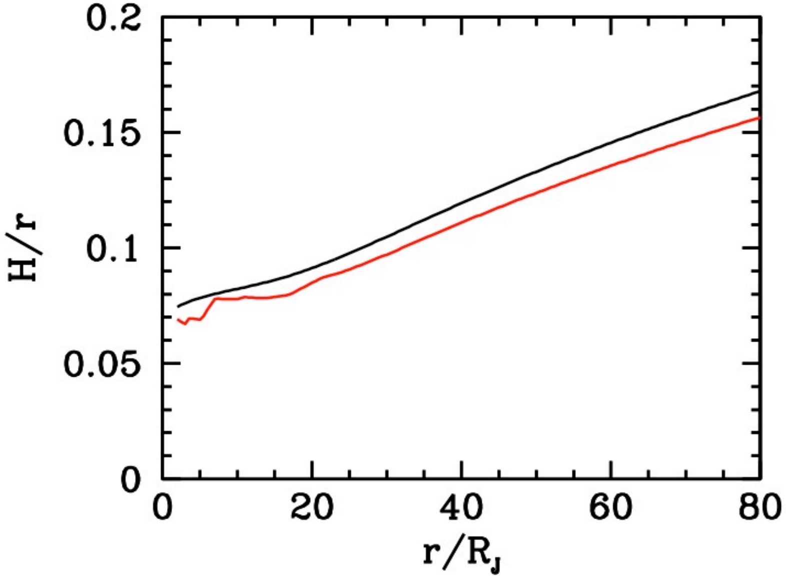
- Improved treatment of low τ_c (optical depth to the midplane) regime and incoming radiation of Jupiter.
- Midplane temperature T_c using
  - – Analytic vertical structure model of Hubeny (1991) for viscous dissipation and isotropic solar nebula irradiation
  - – Extension by Malbet et al. (2001) for irradiation by a central source (i.e. Jupiter).

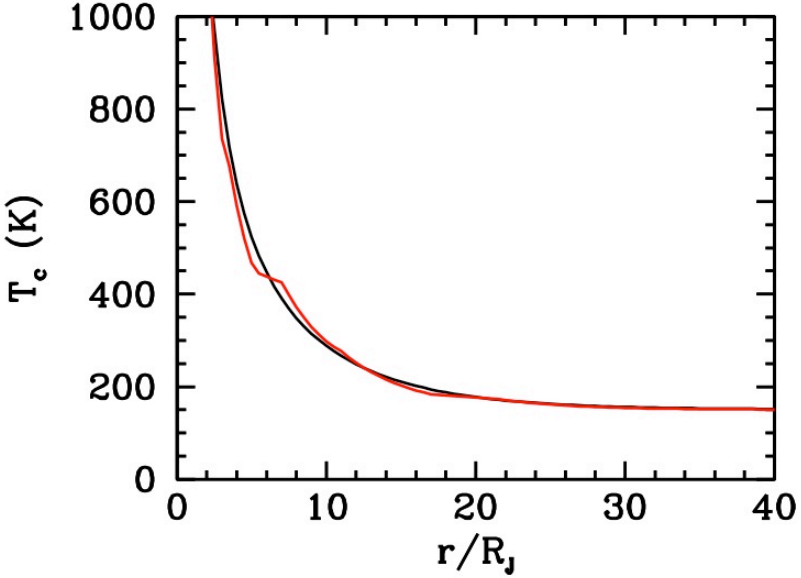
$$\begin{aligned} T_c^4 &= \frac{3}{4}\left[\frac{\tau_c}{2}+\frac{1}{\sqrt{3}}+\frac{1}{3\tau_c}\right]T_d^4+T_{\rm neb}^4 \\ &+\frac{3}{4}\left[\mu_J\left(1-e^{-\tau_c/\mu_J}\right)+\frac{1}{\sqrt{3}}+\frac{1}{3\mu_J}e^{-\tau_c/\mu_J}\right]\left(\frac{\mu_J}{2}\right)\left(\frac{R_J}{r}\right)^2T_J^4, \end{aligned}$$



- Opacity $\kappa = f_{opac}\, \kappa_P$, where κ_P is the Pollack et al. (1994) temperature dependent opacity and $f_{opac} \leq 1$.







- High opacity model:

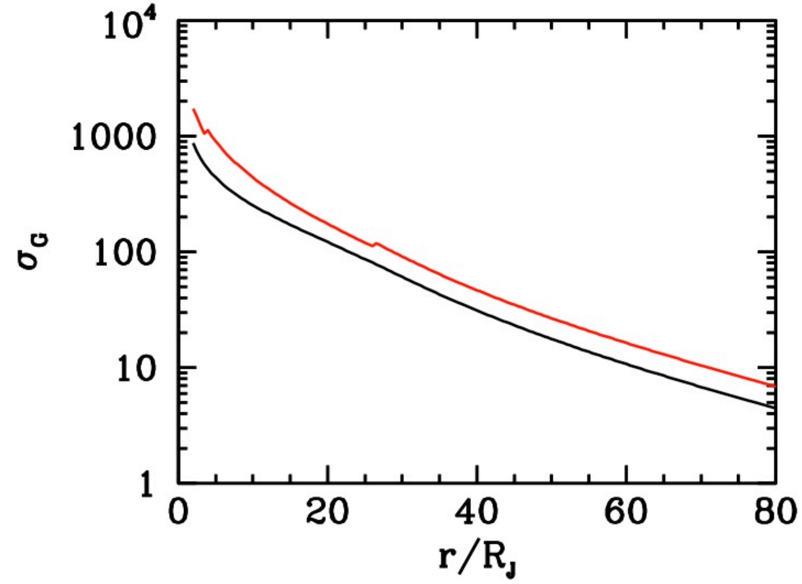
  $f_{\mathrm{opac}} = 1$

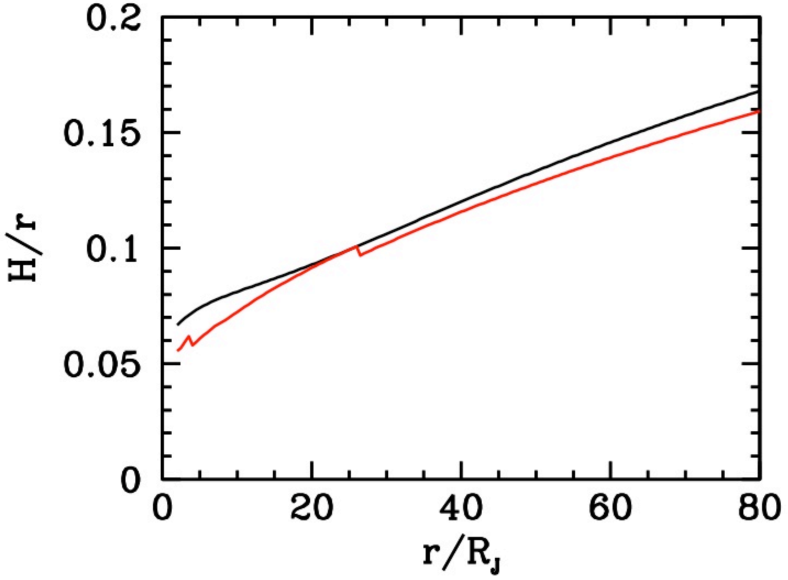
  $\alpha = 5\times10^{-3}$

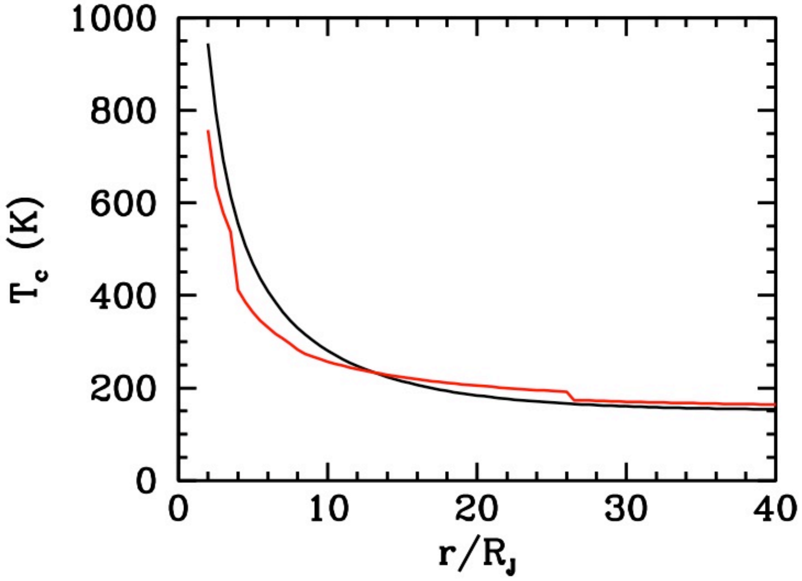
  $\tau_G = 7\times10^{7}$ yr

Red: Improved gas-starved disk model

Black: CW02 model with $\kappa = f_{\mathrm{opac}}$







- Low opacity model:

  $f_{\text{opac}} = 10^{-4}$

  $\alpha = 9\times10^{-4}$

  $\tau_G = 2\times10^7$ yr

Red: Improved gas-starved disk model

Black: CW02 model with $\kappa = f_{\text{opac}}$

Chemical Network Calculations

- Ionization state from chemical network with gas-phase species H_2, H_2^+, Mg, Mg^+, and e^- after Ilgner & Nelson (2006).

Gas Phase Reactions:

- Ionization by interstellar cosmic ray (Umebayashi & Nakano 2009), solar x-ray, and radioisotope decay: $H_2 \rightarrow H_2^+ + e^-$
- Dissociative Recombination: $H_2^+ + e^- \rightarrow H_2$
- Radiative Recombination: $Mg^+ + e^- \rightarrow Mg + h\nu$
- Charge Exchange: $H_2^+ + Mg \rightarrow H_2 + Mg^+$
- The cosmic ray absorbing column ≈ 96 g cm^{-2} and x-ray absorbing column ≈ 8 g cm^{-2}.

Grain Surface Reactions:

- Seven species added to reaction network if dust grains are present: Charged grains G^0, $G^{\pm}$, $G^{\pm 2}$ and adsorbed neutrals $H_2(G)$ and $Mg(G)$.
- Thermal adsorption and desorption of neutrals and ions.
- Grain charging and neutralization in collisions with ions and elections.
- Charge exchange in grain-grain collisions.

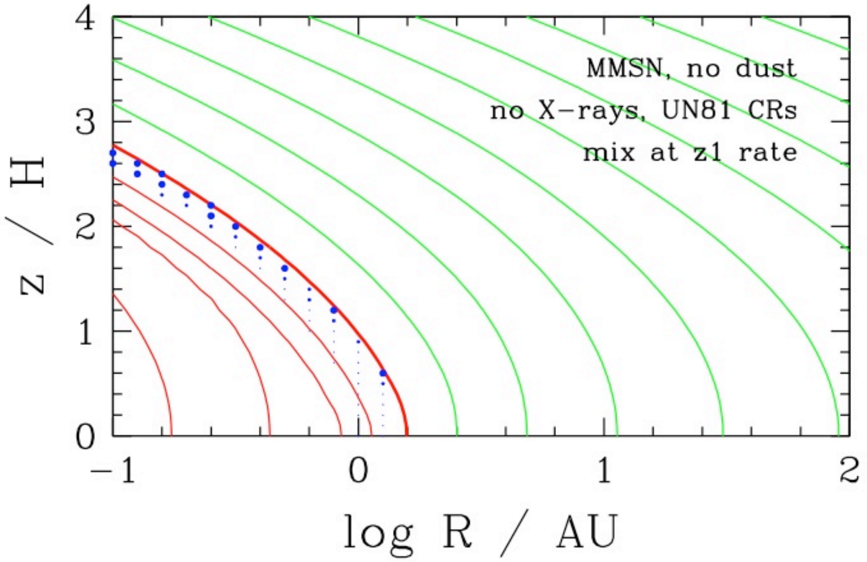
Criteria for Dead Zone

MRI turbulence is absent if both

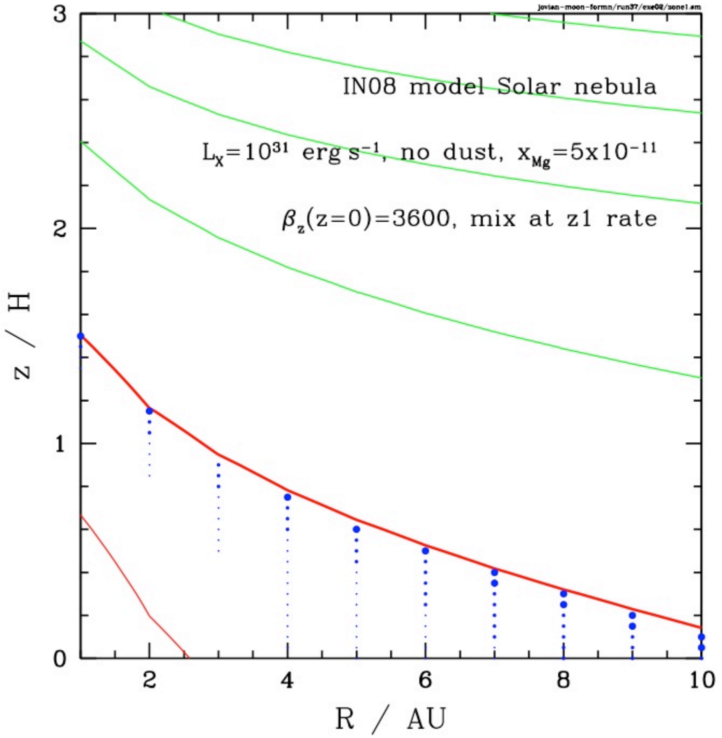
1. The equilibrium ionization is too small (Elsasser number $\Lambda = v_{A,z}^2/(\eta\Omega) < 1$) and
2. The recombination is too fast for ionized gas transported from regions of lower column depth to affect ionization fraction ($t_{rec} < 0.1\ t_{mix}$).

- The $\Lambda < 1$ criterion was established by previous analytic and numerical results (Jin 1996; Sano & Miyama 1999; Sano & Inutsuka 2001; Sano & Stone 2002).

- The $t_{rec} < 0.1\ t_{mix}$ criterion from existing MHD+chemistry simulations of the Solar nebula.



Turner et al. (2007)



Ilgner & Nelson (2008)

- Green contours: $\Lambda > 1$ for equilibrium ionization fraction.
- Red contours: $\Lambda < 1$ for equilibrium ionization fraction.
- Large blue dots: $t_{rec} > t_{mix}$
- Medium blue dots: $t_{mix} > t_{rec} > 0.1\ t_{mix}$

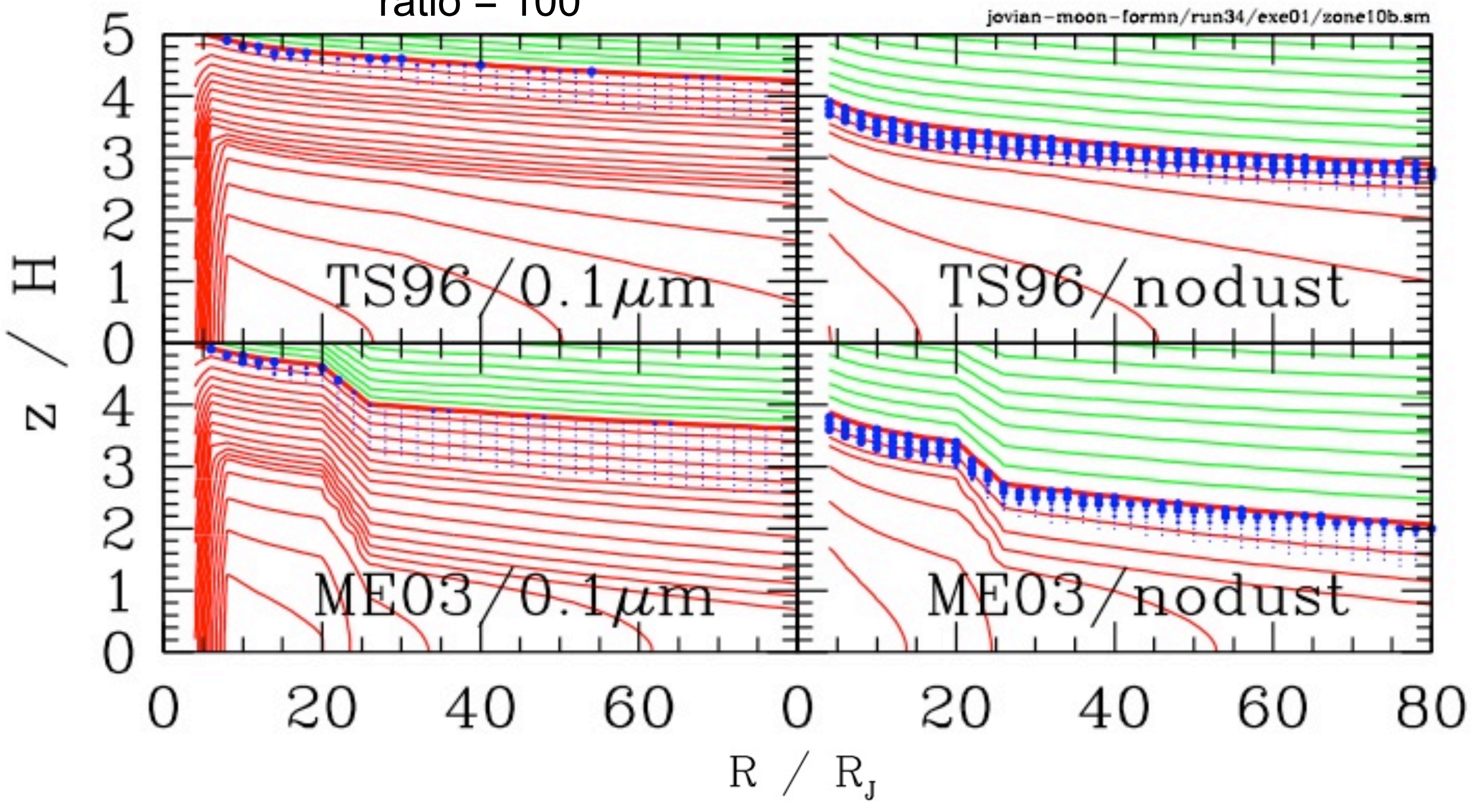
Dead Zone of Minimum Mass Subnebula

0.1μm dust with gas-to-dust ratio = 100

No dust

Takata & Stevenson (1996) models

Mosqueira & Estrada (2003) models



- Mixing can slightly reduce the size of the dead zone if there is no dust.

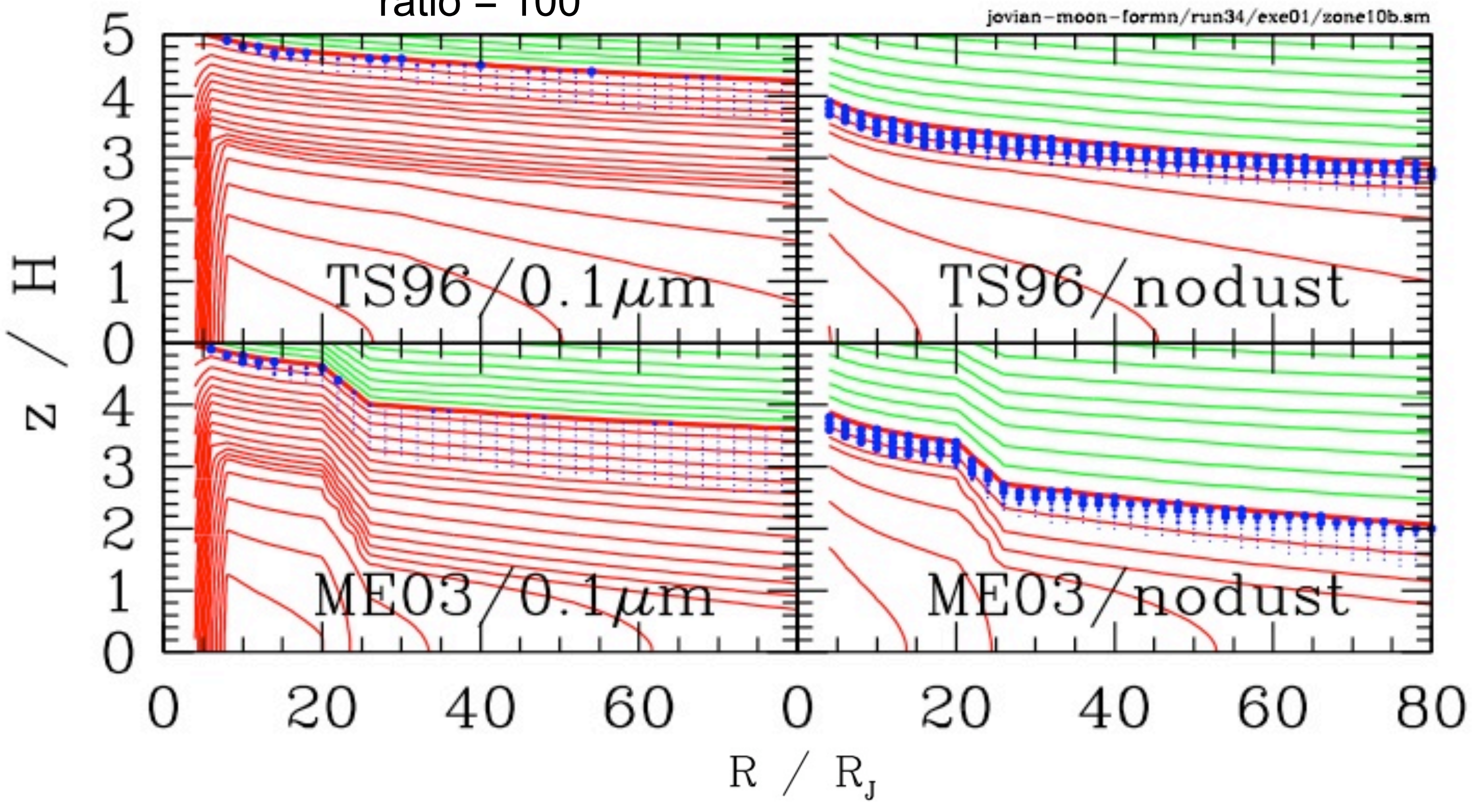
Dead Zone of Minimum Mass Subnebula

0.1μm dust with gas-to-dust ratio = 100

No dust

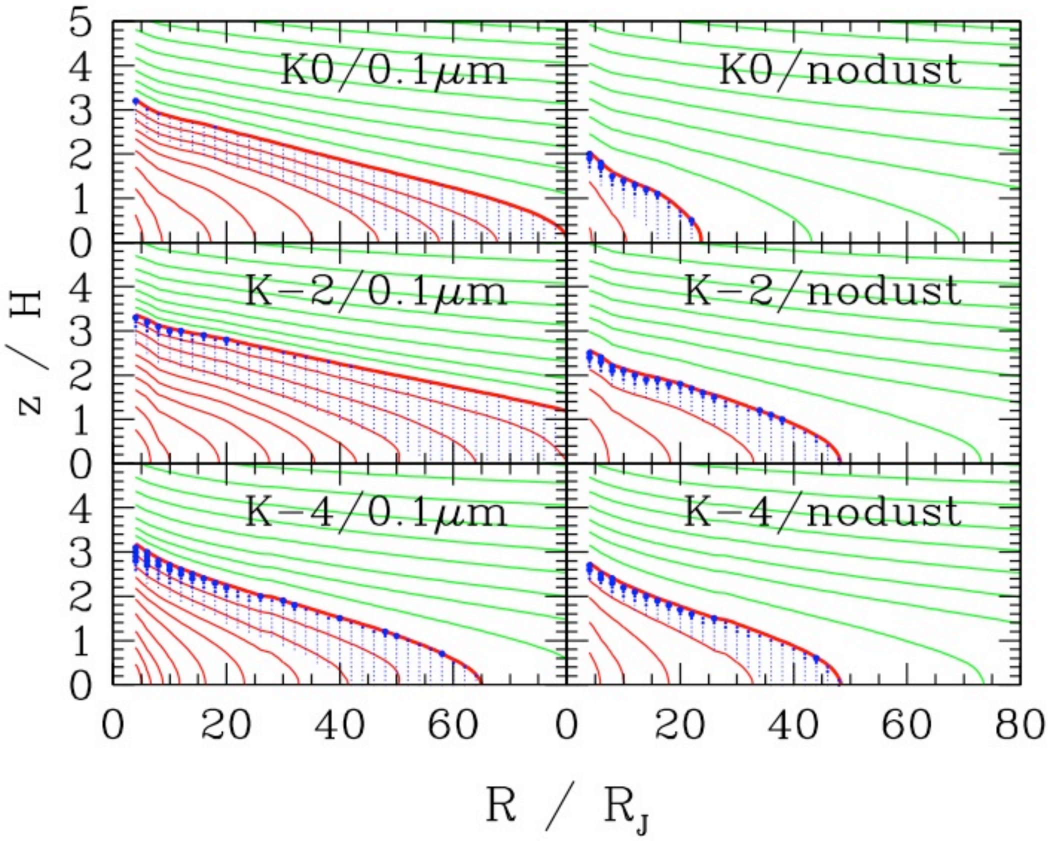
Takata & Stevenson (1996) models

Mosqueira & Estrada (2003) models



- Even with the sharp drop in surface density at $r/R_J \approx 23$ in the Mosqueira & Estrada models, MMSN models are magnetically dead everywhere, except very high in the upper layers.

Dead Zone of Gas-Starved Subnebula



0.1μm dust with gas-to-dust ratio = 100 /f_{opac}

No dust

Opacity = $f_{opac}\ \kappa_P$

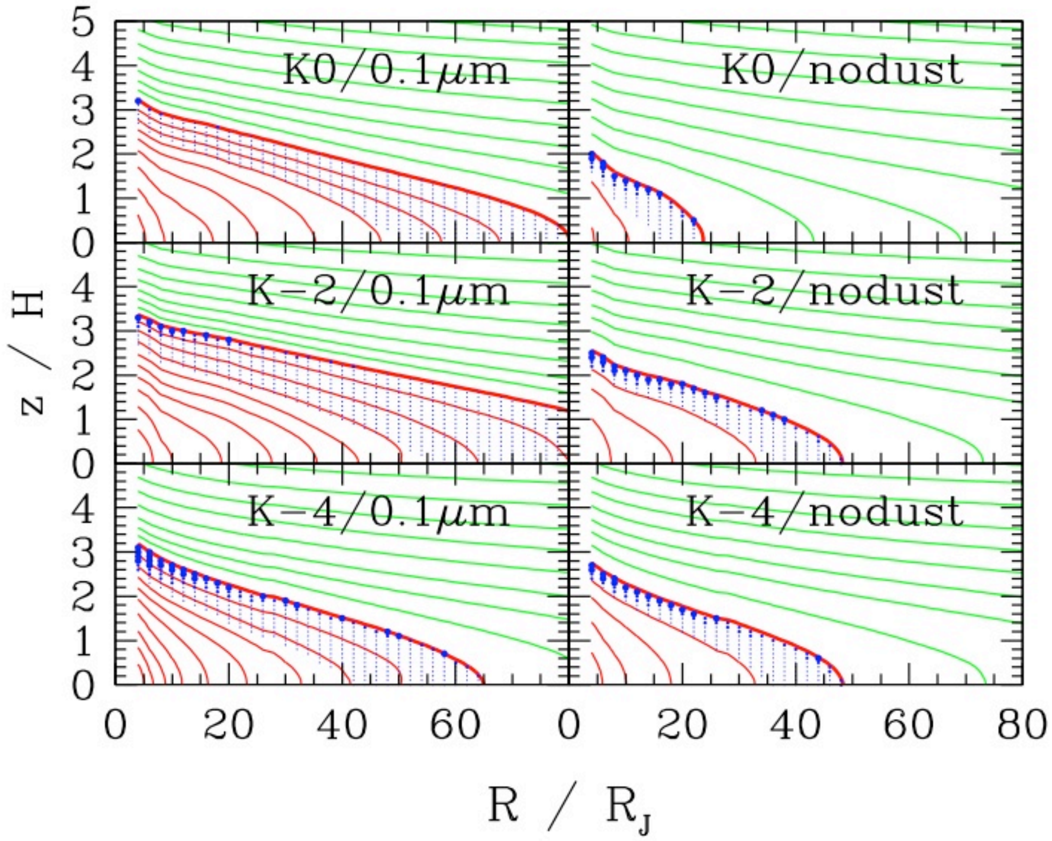
$f_{opac} = 1$

$f_{opac} = 10^{-2}$

$f_{opac} = 10^{-4}$

- Mixing does not significantly affect the size of the dead zone.

Dead Zone of Gas-Starved Subnebula



0.1μm dust with gas-to-dust ratio = 100 /f_{opac}

No dust

Opacity = $f_{opac}\ \kappa_P$

f_{opac} = 1

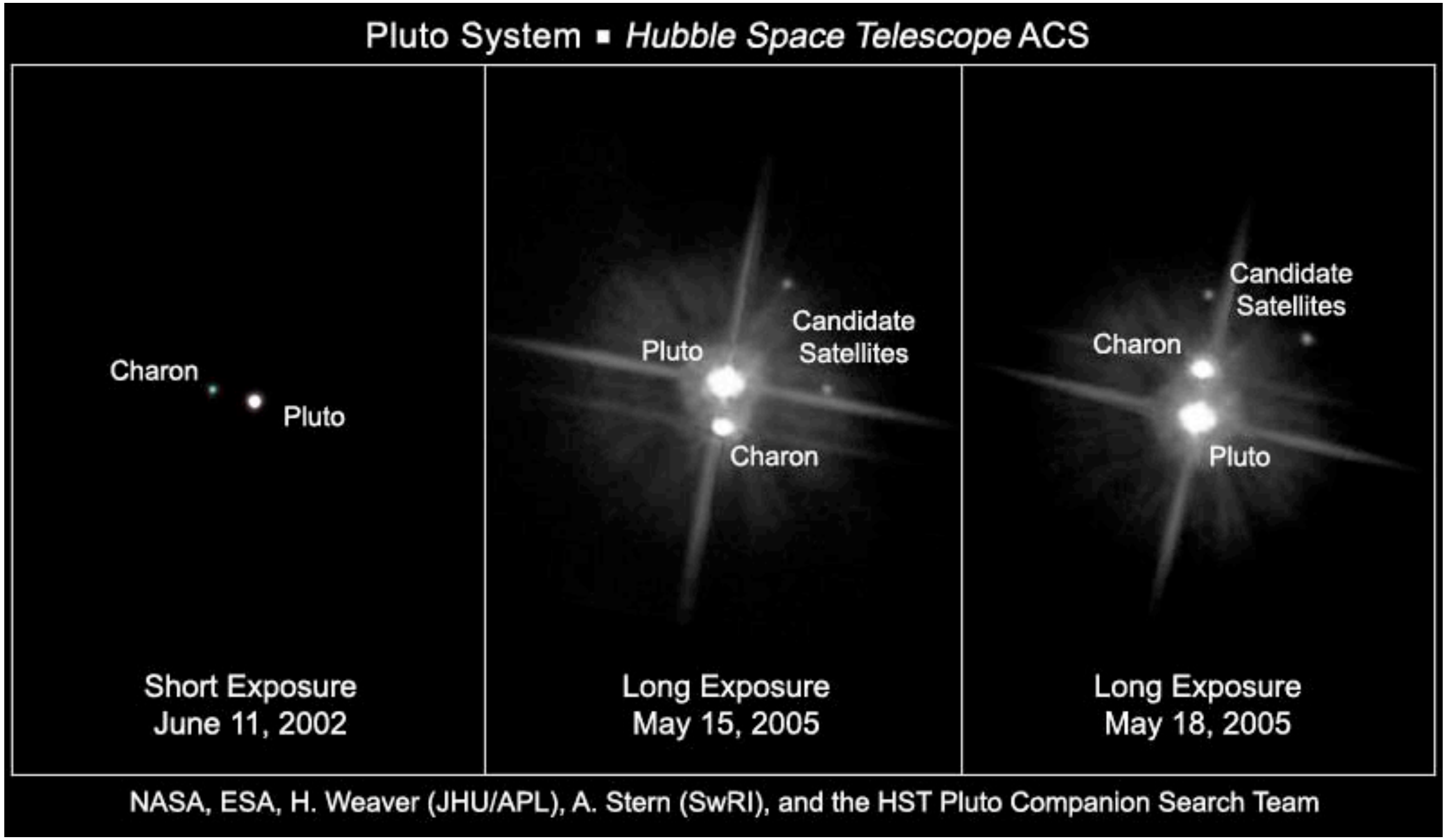
$f_{opac} = 10^{-2}$

$f_{opac} = 10^{-4}$

- No dead zone in the outer regions.
- Dead zone plus active upper layers in the inner regions.

Pluto Satellite System

- Charon was discovered in 1978.
- Two small satellites, Nix and Hydra, were discovered in 2005 by Weaver et al.



NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI), and the HST Pluto Companion Search Team

- Orbits of Nix and Hydra nearly circular and nearly coplanar with that of Pluto-Charon (Buie et al. 2006).
- Orbital periods of Charon, Nix and Hydra nearly in the ratio 1:4:6.
- Orbits of Nix and Hydra significantly non-Keplerian due to
  - large mass ratio of Charon-Pluto
  - proximity of Nix and Hydra to 3:2 commensurability

  (Lee & Peale 2006).

Orbits of 4 bodies in Pluto system about the barycenter as seen from Earth

Point size indicates measurement uncertainties

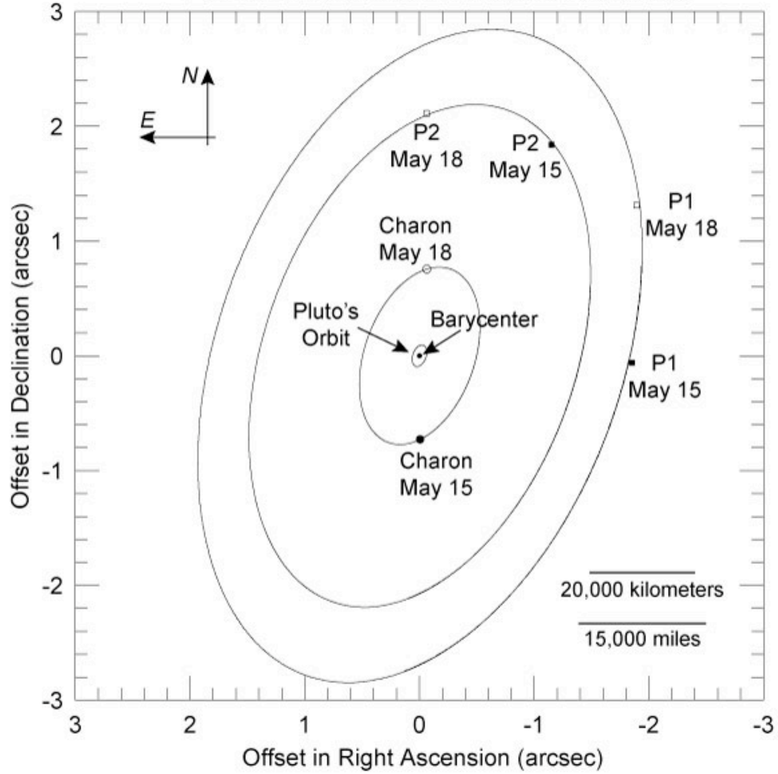
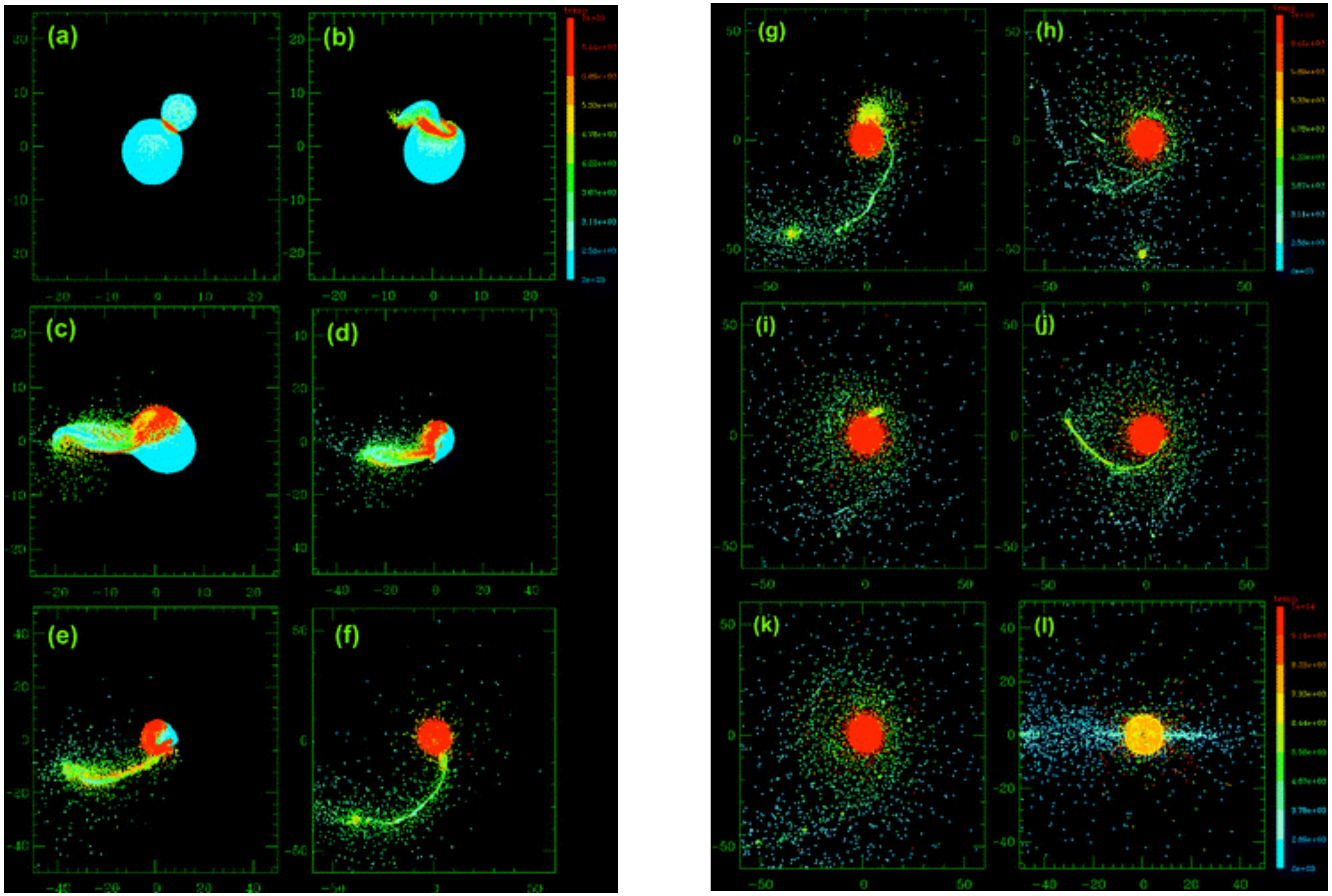


Illustration Credit: *NASA, ESA, W. J. Merline (SwRI), and the Pluto Companion Search Team*

Giant Impact Origin of the Moon

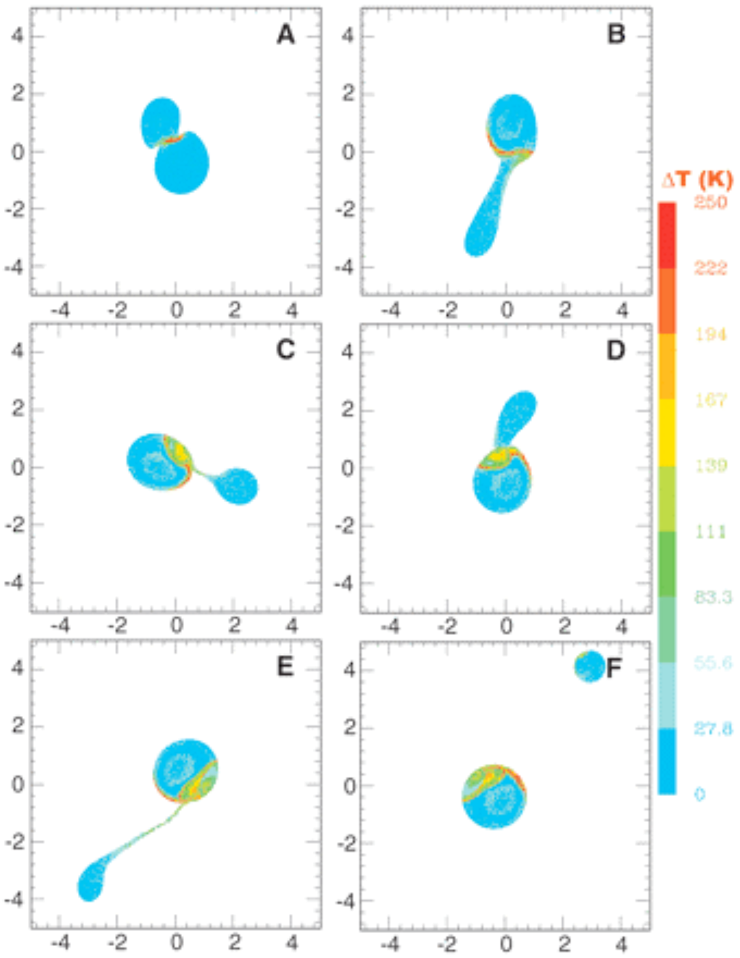
- Moon accreted from impact generated disk.



(Canup 2004)

Impact Origin of the Pluto Satellite System

- Impact captured Charon nearly intact into eccentric orbit with $a_c \sim 4$ R_p.
- Coplanarity: Nix and Hydra were debris from the same impact.
- But debris did not extend beyond ~ 15 R_p.
- Current a = 17, 42, and 56 R_p for Charon, Nix, and Hydra.



(Canup 2005)

Resonant Migration of Nix and Hydra

- Nix and Hydra not in 4:1 and 6:1 resonances with Charon at present.
- But Nix and Hydra could once be in these resonances and were pushed out as Charon's orbit expanded due to tidal evolution (Ward & Canup 2006).

- Stable transport of Nix and Hydra in 4:1 and 6:1 as a_c increases by a factor of ~ 4 is difficult:
  - Ward & Canup (2006): Nix and Hydra trapped in corotation resonance only , which does not excite eccentricity.
  - Charon's eccentricity e_c must be maintained during most of the orbital expansion to maintain stability of resonance.
  - Lithwick & Wu (2007):

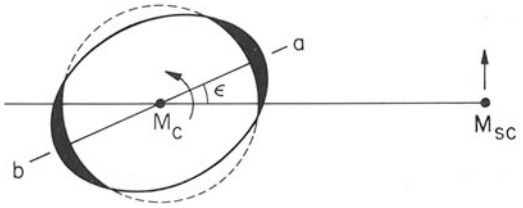
    To transport Nix, $e_c <\sim 0.024$

    To transport Hydra, $e_c >\sim 0.8\ R_p/a_c$

    Both cannot be satisfied at the same time.

Tidal Evolution of Pluto-Charon

- Need evolution of Charon's orbit (in particular e_c) for resonant migration problem.
- Previous study of tidal evolution of Charon's orbit assumed circular orbit (Dobrovolskis et al. 1997).
- Tidal Models:
  - Constant time lag Δt: closed expressions valid for large e (Mignard 1980; Hut 1981).
  - Constant dissipation function Q (Goldreich & Soter 1966)
  - Tides on both Pluto and Charon
  - Non-zero $C_{22} = (B-A)/(4MR^2)$: Permanent non-axisymmetric deformation



$$\frac{1}{n}\left\langle\frac{d\dot{\psi}_i}{dt}\right\rangle = \frac{3G}{C_i a^6}k_{2i}\Delta t_i M_j^2 R_i^5\left[f_1(e^2) - f_2(e^2)\frac{\dot{\psi}_i}{n}\right],$$

$$\frac{1}{a}\left\langle\frac{da}{dt}\right\rangle = \frac{6G}{\mu a^8}k_{2P}\Delta t_P M_C^2 R_P^5\left\{\left[\frac{\dot{\psi}_P}{n}f_1(e^2) - f_3(e^2)\right] + A\left[\frac{\dot{\psi}_C}{n}f_1(e^2) - f_3(e^2)\right]\right\},$$

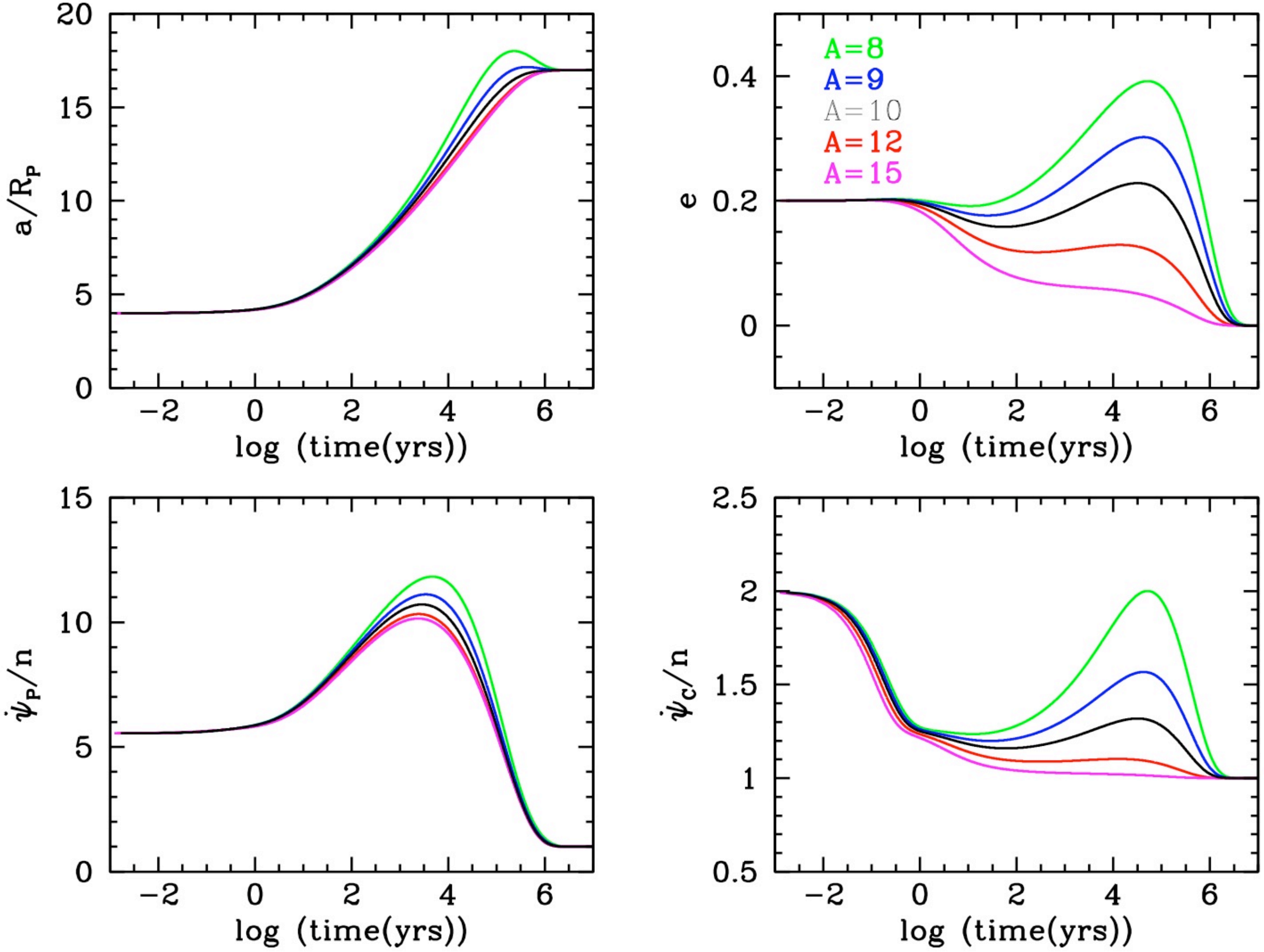
$$\frac{1}{e}\left\langle\frac{de}{dt}\right\rangle = \frac{27G}{\mu a^8}k_{2P}\Delta t_P M_C^2 R_P^5\left\{\left[\frac{11}{18}\frac{\dot{\psi}_P}{n}f_4(e^2) - f_5(e^2)\right] + A\left[\frac{11}{18}\frac{\dot{\psi}_C}{n}f_4(e^2) - f_5(e^2)\right]\right\};$$

where

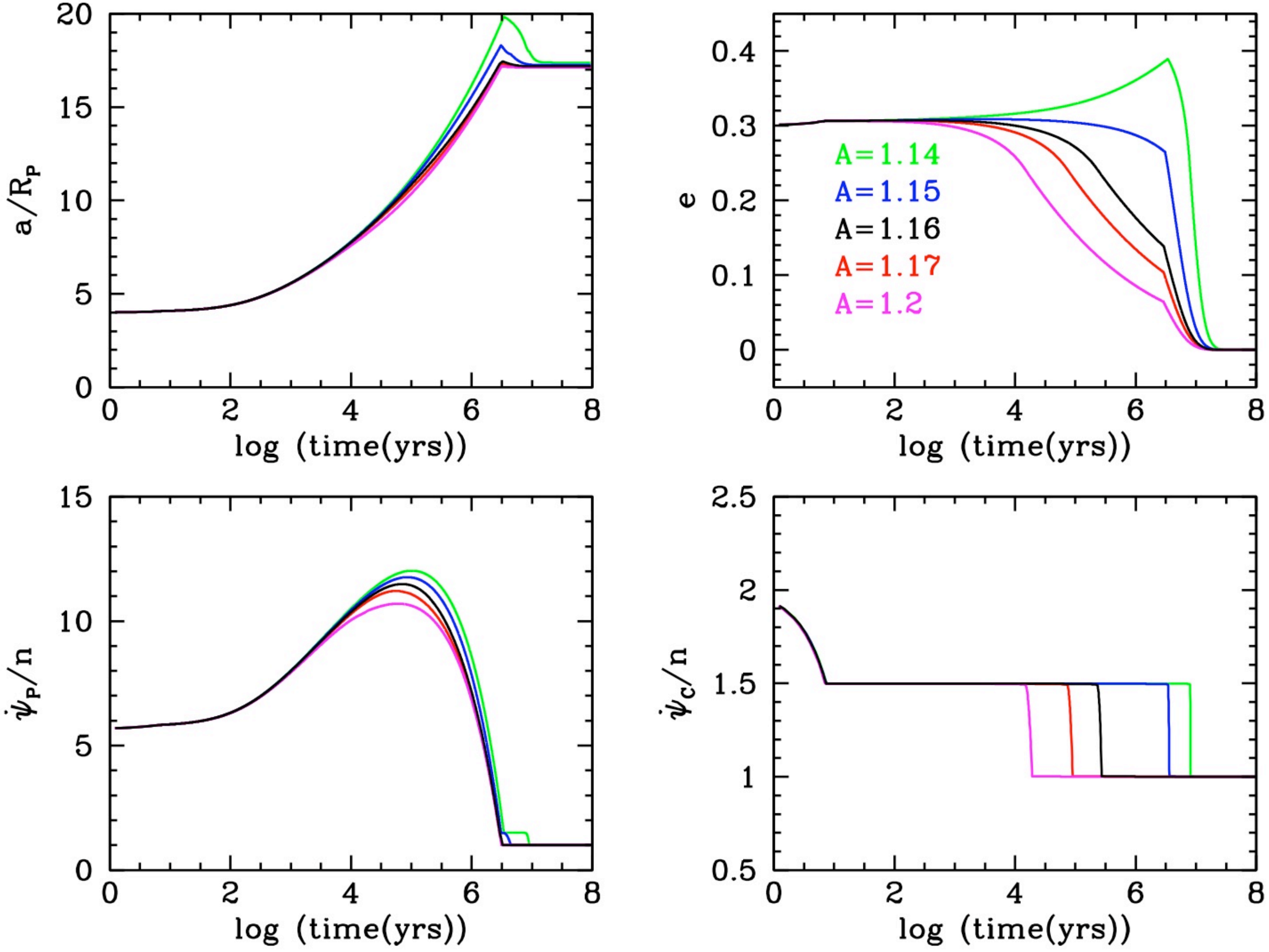
$$A = \frac{k_{2C}}{k_{2P}}\frac{\Delta t_C}{\Delta t_P}\left(\frac{M_P}{M_C}\right)^2\left(\frac{R_C}{R_P}\right)^5$$

- $A \approx (\mu_p\, \Delta t_c\, R_c)/(\mu_c\, \Delta t_p\, R_p)$ is a measure of relative rates of tidal dissipation.

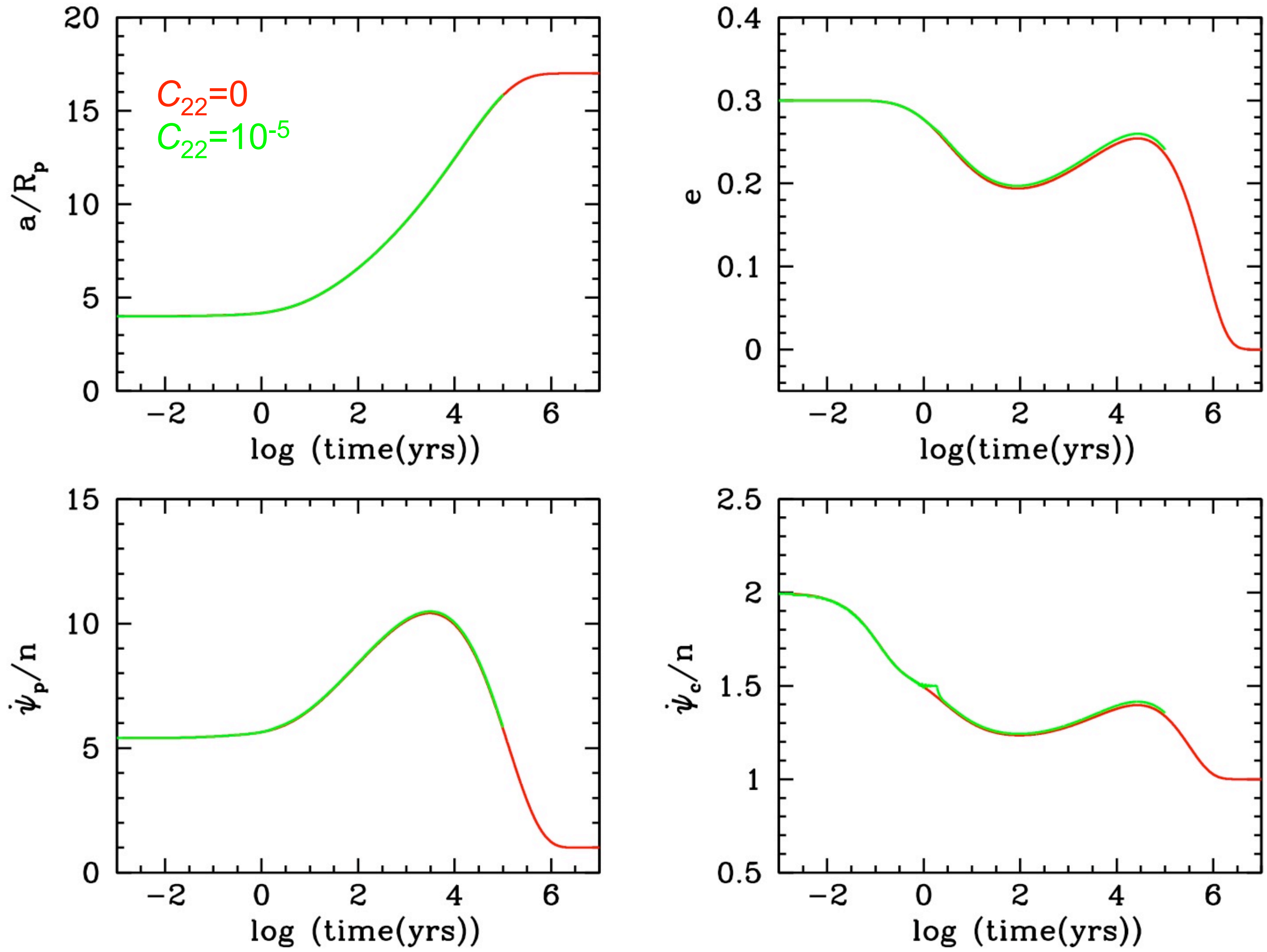
k_{2p} =0.058, Δt_p = 10 mins



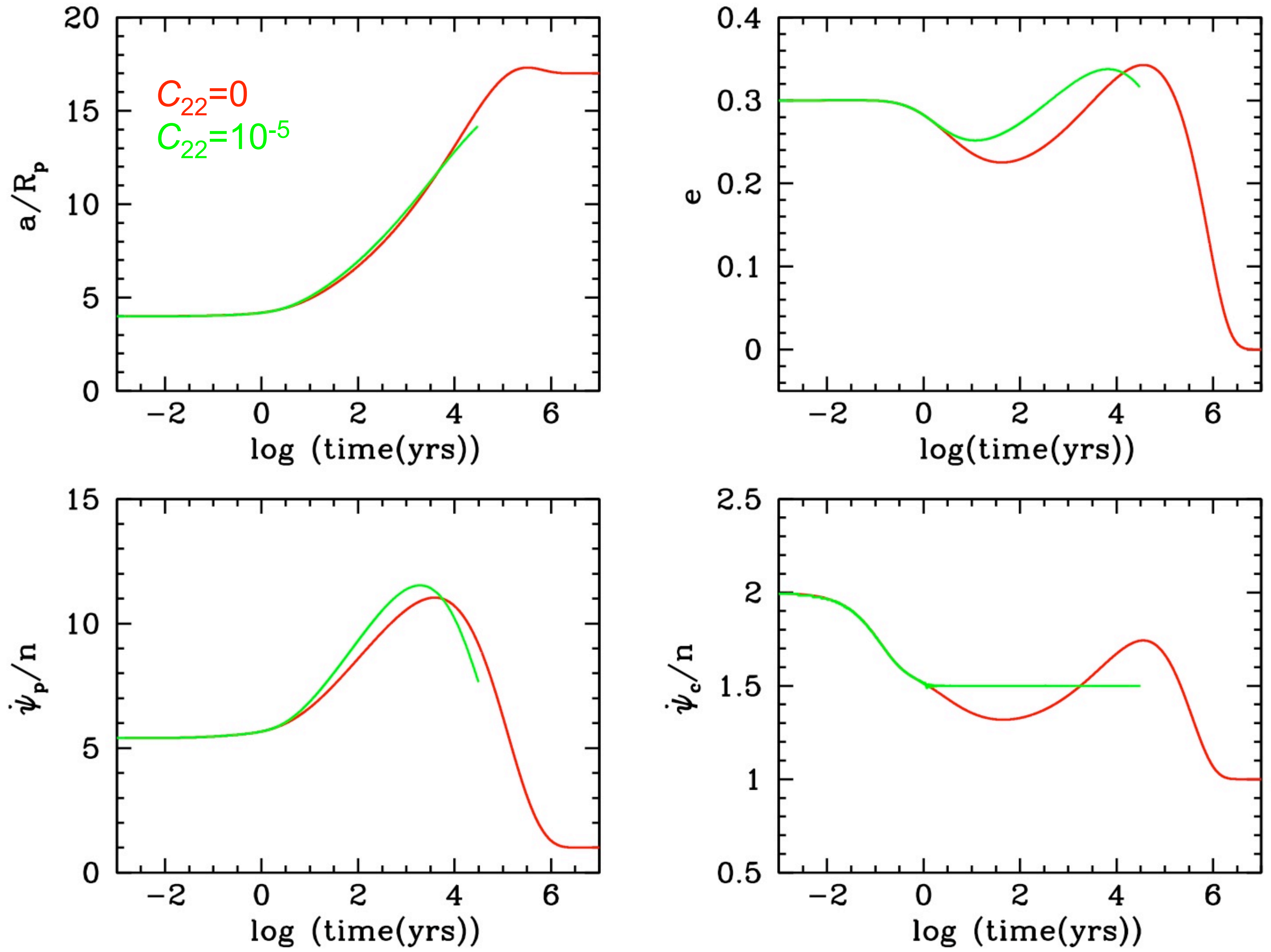
k_{2p} =0.058, Q = 100



k_{2p} =0.058, Δt_{p} = 10 mins, A = 10



k_{2p} =0.058, Δt_p = 10 mins, A = 9



Summary (I)

- We have developed criteria for estimating the size of the dead zone from chemical network calculations.
- Minimum Mass Subnebula models of the circumjovian disk are magnetically dead everywhere, except very high in the upper layers.
- Gas-starved Subnebula models are similar to solar nebula models:
  - No dead zone in the outer regions
  - Dead zone plus active upper layers in the inner regions.

Summary (II)

- Tidal evolution of Pluto-Charon shows complex behaviors: pseudo-synchronous rotation, 3:2 spin-orbit resonance, semimajor axis overshooting
- Can a consistent history of the Pluto satellite system be constructed based on intact capture of Charon and resonant migration of Nix and Hydra?